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TITLE: Multidimensional MHD Simulations of Shock Formation in Plasmas.

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14. ABSTRACT
The Air Force requires new technical capabilities to control the flight characteristics of planned hypersonic aircraft. The plasma actuator concept offers the possibility to quickly maneuver a hypersonic vehicle merely by switching on or off the generation of a lightly ionized air plasma along panels embedded in the aircraft's skin. The goal of this basic research effort is to harness the state-of-the-art in multidimensional plasma modeling capabilities to better understand the basic physics of the plasma dynamics that can impact aerodynamic shock fronts. MHD plasma modeling algorithms will be added to existing, proven multidimensional aerodynamics codes provided by Prof Zha of Miami's Aeronautical Engineering Department. This resultant new simulation capability will then be used to more accurately model the plasma actuator concept that is already being studied under this grant using the less-accurate MAGIC code.

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Research Objectives

Our research objective is to apply the methods of Computational MHD to multidimensional situations in which shocks play an important role. In space plasmas we have worked on a possible heating mechanism in the solar corona due to Alfvn shocks. In flight dynamics these include the effects of magnetic fields and plasma formation in hypersonic flows around blunt bodies. Since the start of our work we have included the study of dielectric barrier discharges (DBD) for their possible application as plasma actuators.

The computer cluster

We received a DURIP equipment grant in 2006 to build a parallel computer to make possible the study of 2 and 3 dimensional MHD problems. During the first year of this grant we purchased and assembled a parallel computer cluster that consisted of 50 nodes, with double dual core Intel Xeon 5150 processors (4 processors per node), for a total of 200 processors. Each node has 4 Gigabytes of memory and 80 Gigabytes of disk. The master node has a 1.6 Terabytes RAID 5 disk array. We communicate with the cluster via three workstations. Two of them have double dual core Intel Xeon 5160 processors, and a 2 Terabytes RAID 5 disk array each. The third workstation has double dual core Intel Xeon 5150 processors and a 1/2 Terabytes RAID 5 disk array. Since then we have added four more nodes contributed by Prof. Gundersen of our astrophysics group, so now there are 216 processors. The 1.6 TB main hard disk is not sufficient, so thanks to supplemental funding, we have added another 6TB to our RAID array. During the third year of the grant the cluster has been used to run a lot of CFD simulations as described below. It has also been used to test the parallelized LINUX version of MAGIC. After much work, with the help of ATK Missions Inc. people, and our own system manager, Marco Monti, we now have MAGIC running in the cluster.

Accomplishments in Low Magnetic Reynolds MHD hypersonic flow

At the beginning of the project I worked with Dr. C. G. Boynton using the full MHD code FCTMHD3D, which is a parallelized code, but we abandoned it because we could not adapt it to run with complicated boundaries like airfoils. Since 2007 we have been running in our cluster the sophisticated parallelized CFD codes developed by the research group of Prof. Gecheng Zha of our Aerospace engineering department , and to modify that code to include the MHD equations. This work has been done mostly by a graduate student, Mr. Jaejin Lee. Many research groups are working on the problem of MHD hypersonic flows, and we are newcomers, so we are playing catch-up. After much difficulty we have succeeded in running our code at high Mach numbers with a magnetic field in the usual low magnetic Reynolds MHD number approximation (low conductivity), which neglects the magnetic fields generated by the small plasma currents. We have not yet included plasma chemistry, so the electrical electrical conductivity we use is fitted from other work. We presented AIAA-2009-459[1] paper at the January 2009 AIAA conference in Orlando, with results for the 2D problems of hypersonic flow around flat plates and airfoils. Figs. 1 and 2 below are from Ref. [1] and show some results for MACH 10 flow. We are presently working on the 3D model of flow around a blunt body. We have overcome our difficulties in setting up a 3D computational grid using GRIDGEN software. Figs. 3 and 4 show some 3D results. So far our model has not incorporated air chemistry, so the temperatures we generate are too high, as can be seen in Figs. 1 and 2, and also in Fig. 4. At this time, rather than incorporating the usual air chemistry problem in terms of the usual 11 gas species, we are

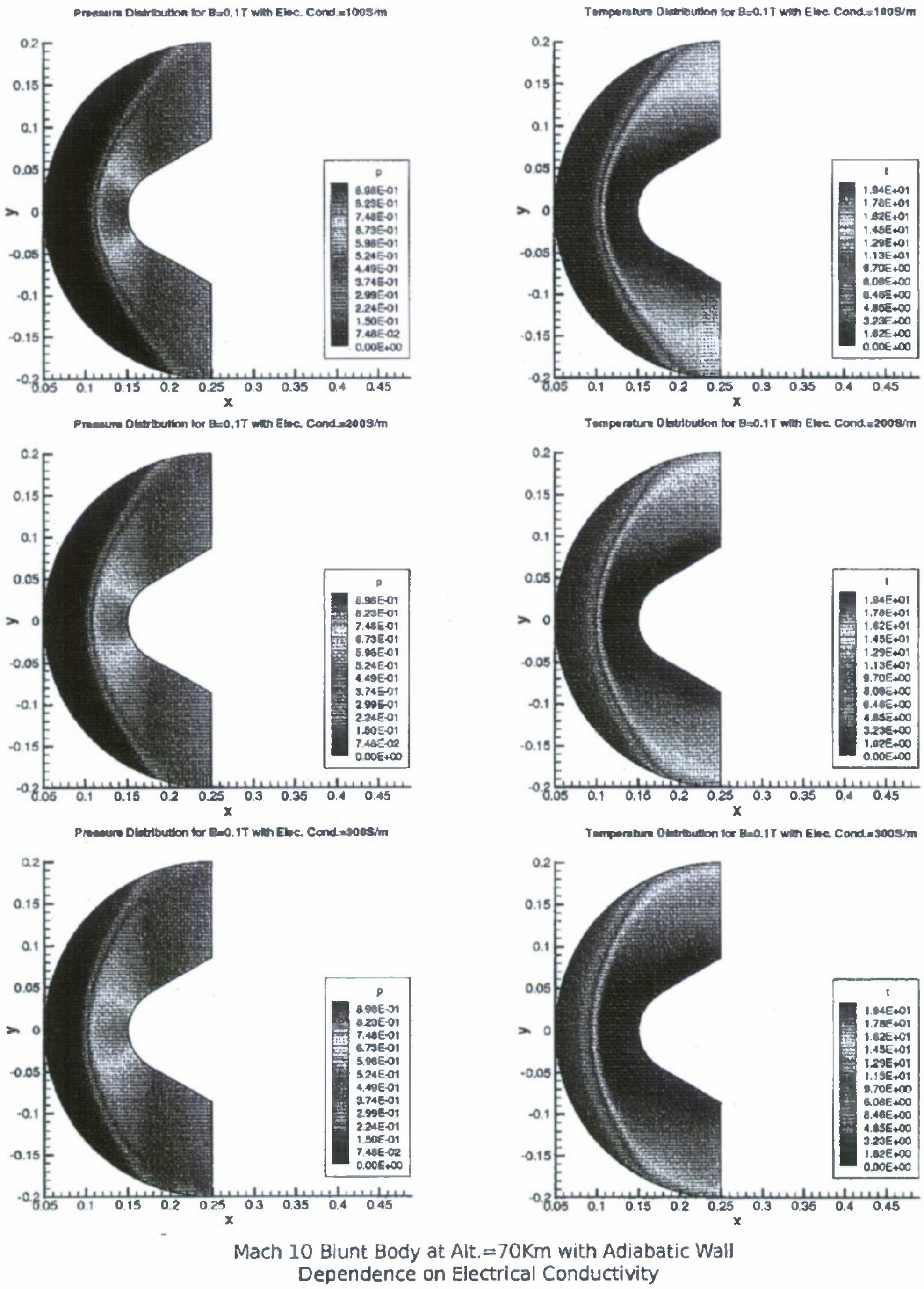

Figure 1: Variation of flow properties as a function of magnetic field strength

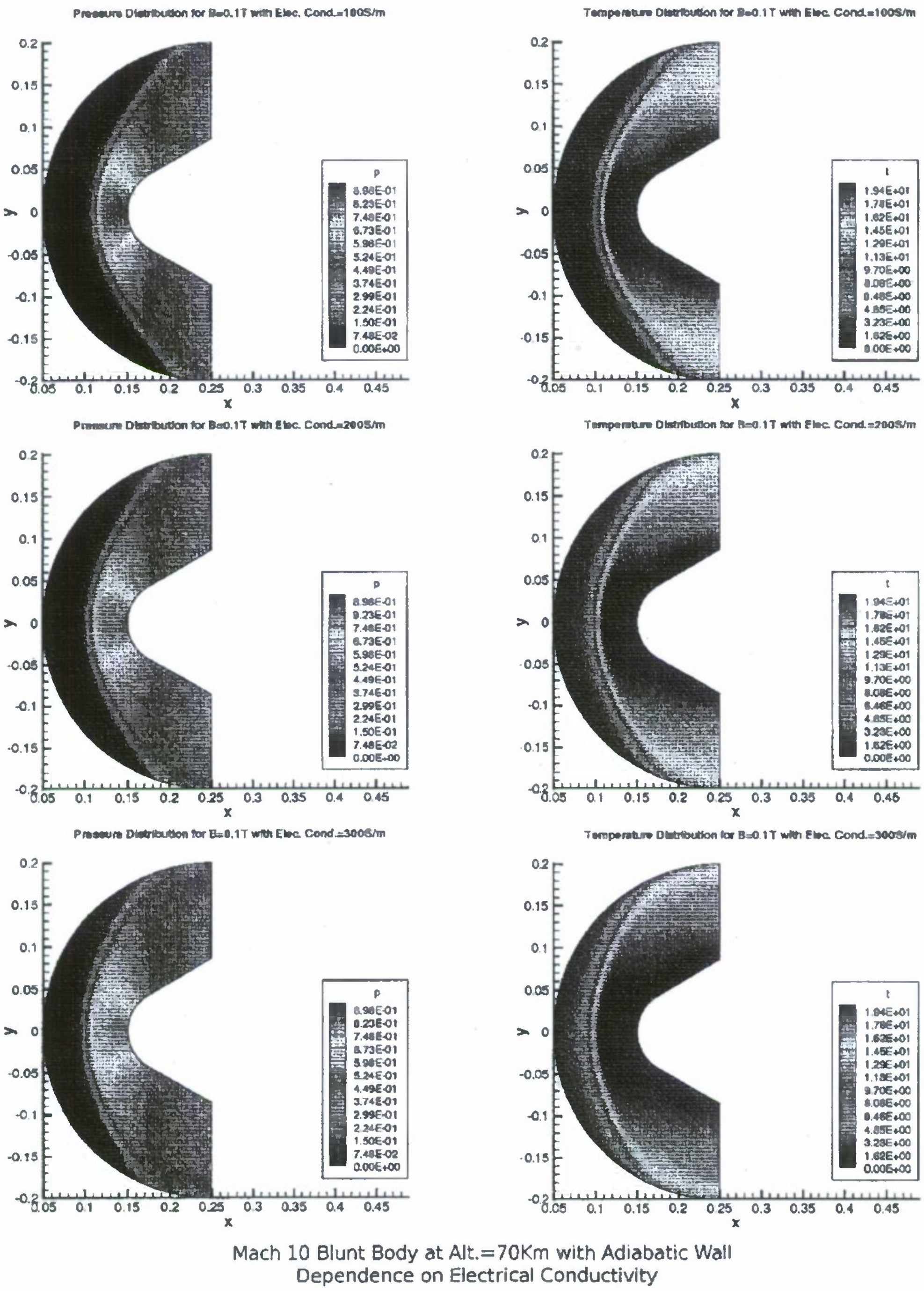

Figure 2: Variation of flow properties as a function of electrical conductivity starting to use the method where the real high temperature air thermodynamic properties are calculated using the TGAS[2] code developed by NASA.

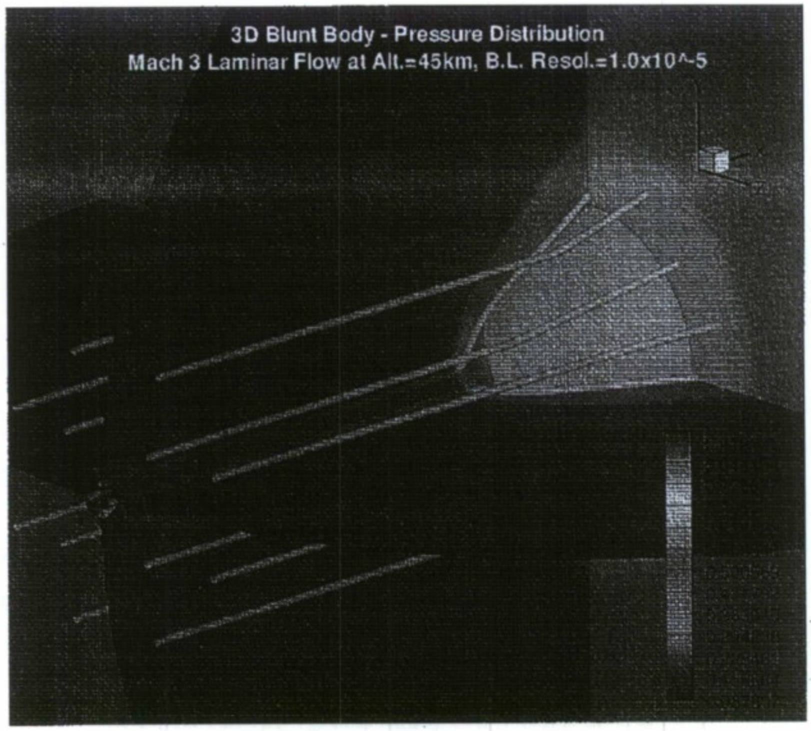

Figure 3: Streamlines and pressure field in 3D flow around a symmetrical blunt body

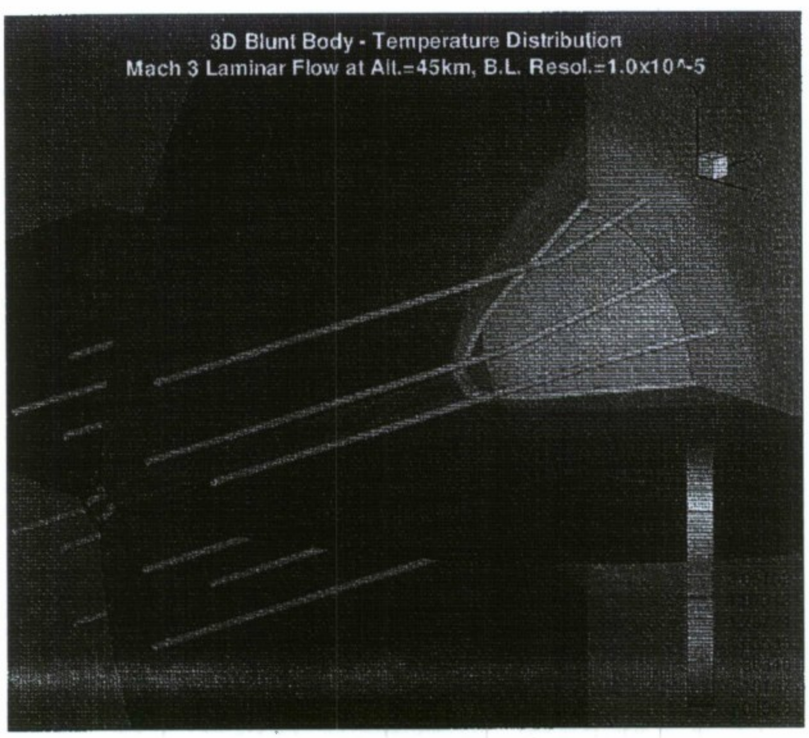

Figure 4: Streamlines and temperature field in 3D flow around a symmetrical blunt body

Accomplishments in DBD plasma actuators

Starting with the Las Vegas workshop in March 2007 I have been seriously involved with the PIC code MAGIC to study dielectric barrier discharges (DBD) and their effects on boundary layer flows. This code runs on Windows, so I use the laptop bought with grant funds, and also on Linux, so I also run 2D simulations in the work station obtained with

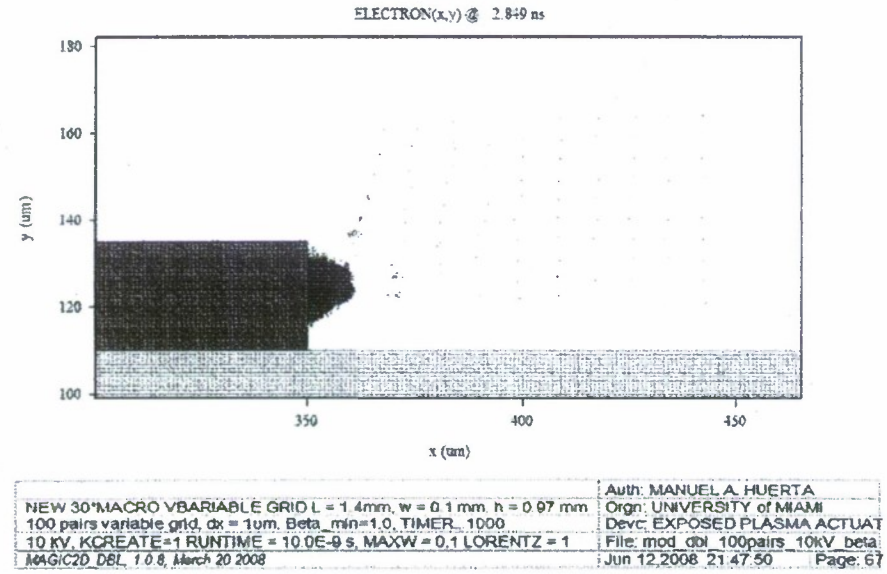

Figure 3. Enlarged view of some 2.5×10^6 macroelectrons in space near the exposed anode at $t \approx 2.849$ nanoseconds,almost at the end of the simulation.

grant funds. At this point 3D MAGIC is parallelized, and runs on our cluster, but 2D MAGIC is not yet parallelized. So far we have only been running 2D simulations using

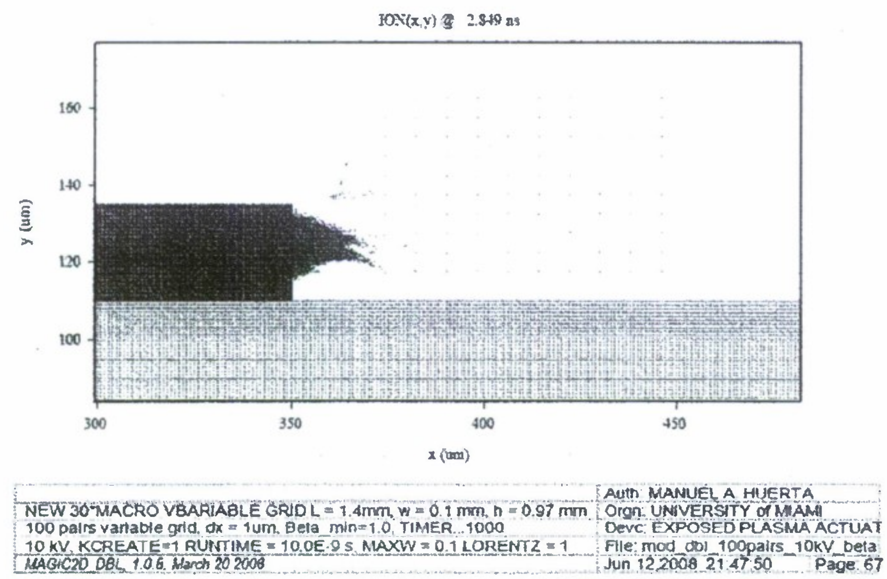

Figure 4. Enlarged view of of some 2.5×10^6 N_2^+ macroions in space near the exposed anode at $t \approx 2.849$ nanoseconds, almost at the end of the simulation.

one processor for durations of the order of 1 nanosecond because of the long CPU time and because large numbers of particles fill the memory of one processor. In 2007 I presented PPPS - 2007 - 912 poster paper at the June 17 - 22 IEEE conference in Albuquerque and I gave a talk at the Albuquerque MAGIC workshop. I also presented the oral paper AIAA-2008 -3791 on this work at the AIAA conference in Seattle June 23 - 27 2008. Finally I presented the oral paper AIAA-2009-652 at the Orlando AIAA conference, from January 5 - 8, 2009. Figures 3 and 4 are taken from the Orlando paper. Now that MAGIC runs in our parallel computer, the P. I. is starting to develop 3D simulations to run in the parallel cluster. These could run for longer times, not just because of the faster speed of computing, but because an individual processor would only look at a part of the computational region, so would not have to carry so many particles, and its memory should not fill up so soon. I have found it frustrating that results do not tend to agree when some of the parameters in MAGIC are changed. This is a long story but recently, since the 2009 workshop I have been able to get agreement of results using certain modifications of the code. In conversations with Dr. Lars Ludeking, of ATK Mission Systems Group, I have made it clear that MAGIC needs many improvements to be able to treat plasma problems. The main changes have to do with the IONIZATION command.

Status of Efforts

In the future we should include the high temperature air chemistry in our MHD code. We also want to add to the code the full MHD equations, not simply the low magnetic Reynolds number approximation. So far I have not assigned a graduate student to help me with the plasma work using MAGIC because at this point that seems like a risky thing for a graduate student to work on for a Ph. D. dissertation. The work on MAGIC has started to look better after the 2009 workshop in Las Vegas, however, and I am hopeful that real progress can be made after the people at ATK Mission Systems Group make the needed improvements. In this regard, Dr. Robert Vidmar, of the University of Nevada at Reno, is collaborating in guiding what air chemistry processes are needed in a version of MAGIC that could hope to agree with experiments in air.

Personnel Supported

The P.I. was supported by grant funds during the summers of 2006, 2007, and 2008. In 2006 - 2008 Dr. Boynton was supported for a total of about 9 months. My graduate student J. Lee has been supported full time for the entire grant period. Miss Dhayal was supported for 8 months. Unfortunately, after she had taken courses in CFD and plasma physics, she failed the Physics Deprtment's Ph. D. qualifying exam for the second time. For that reason the department faculty voted to terminate her as a graduate student, and I dropped her from my project. Two undergraduate students, Mr. Julien Lhermitte and Mr. Alain De Verneil also received grant support.

Conferences Attended

[1.] The P. I. attended the 44th AIAA Acrospace Sciences Meeting in Reno, Nevada, 7 - 11 January, 2007. We did not present any work here, but learned a lot about plasma actuators and hypersonic MHD flow.

[2.] The P. I. attended the MAGIC workshop in Las Vegas, Nevada, 12 - 16 March, 2007 to learn how to use the PIC code MAGIC fro for plasma physics problems.

[3.] The P. I. attended the 34th IEEE International Pulsed Power and Plasma Science Conference, 17 - 22 June, 2007, Albuquerque, New Mexico. The P. I. presented two poster papers and gave a talk at the concurrent MAGIC workshop.

[4.] The P. I. and two graduate students attended the 38th AIAA Plasmadynamics and Lasers Conference in conjunction with the 16th International Conference on MHD Energy Conversion, 25 - 28 June, 2008, Miami, Florida. We presented no papers.

[5.] The P. I. attended the 45th AIAA Aerospace Sciences Meeting in Reno, Nevada, 7 - 11 January, 2008. We did not present any work here, but learned a lot about plasma actuators and hypersonic MHD flow.

[6.] The P. I. attended the MAGIC workshop in Las Vegas, Nevada, 24 - 28 March, 2008. The P.I. improved his skill in using this code for plasma physics problems.

[7.] The P. I. presented the oral paper paper AIAA 2008-3791 titled "Study of Dielectric Barrier Discharges Using the Particle in Cell Code MAGIC", by M. A. Huerta, L. Ludeking, in *Proceedings of the 39th AIAA Plasma dynamics and Lasers Conference*, 23-26 June 2008, Seattle, Washington.

[8.] The P. I. and a graduate student presented a paper at the 47th AIAA Aerospace Sciences Meeting, 5-8 January 2009, Orlando, Florida

Publications

1. M. A. Huerta, J. Orta, and C. G. Boynton, "One Dimensional Simulations of MHD Shock Heating of a Stratified Solar Coronal Hole", in Proceedings of the 34th IEEE International Pulsed Power and Plasma Science Conference, 17 - 22 June, 2007, Albuquerque, New Mexico, paper PPPS 2007 - 1599.

2. M. A. Huerta, L. Ludeking, "Progress in Two Dimensional Particle in Cell Simulations of Dielectric Barrier Discharges for Plasma Actuators", paper PPPS - 2007 - 912 in *Proceedings of the 34th IEEE International Pulsed Power and Plasma Science Conference*, 17 - 22 June, 2007, Albuquerque, New Mexico.

3. M. A. Huerta, L. Ludeking, "Study of Dielectric Barrier Discharges Using the Particle in Cell Code MAGIC", paper AIAA 2008-3791 in *Proceedings of the 39th AIAA Plasma dynamics and Lasers Conference*, 23-26 June 2008, Seattle, Washington.

4. M. A. Huerta, L. Ludeking, "Some Results of Dielectric Barrier Discharge Simulations Using the PIC Code MAGIC", paper AIAA 2009-652 in *47th AIAA Aerospace Sciences Meeting*, 5 - 8 January 2009, Orlando, Florida.

5. J. Lee, M. A. Huerta, and G. Zha, "Low Magnetic Reynolds Number Hypersonic MHD Flow Using E-CUSP WENO Schemes", paper AIAA-2009-459 in *47th AIAA Aerospace Sciences Meeting*, 5 - 8 January 2009, Orlando, Florida.